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Spatial variation in the flux of atmospheric deposition and its ecological effects in arid Asia

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ABSTRACT

Atmospheric deposition is one of the key land surface processes, and plays important roles in regional ecosystems and global climate change. Previous studies have focused on the magnitude of and the temporal and spatial variations in the flux of atmospheric deposition, and the composition of atmospheric deposition on a local scale. However, there have been no comprehensive studies of atmospheric deposition on a regional scale and its ecological effects in arid Asia. The temporal and spatial patterns, composition of atmospheric deposition, and its potential effects on regional ecosystems in arid Asia are investigated in this study. The results show that the annual deposition flux is high on the Turan Plain, Aral Sea Desert, and Tarim Basin. The seasonal deposition flux also varies remarkably among different regions. The Tarim Basin shows higher deposition flux in both spring and summer, southern Mongolian Plateau has a higher deposition flux in spring, and the deposition flux of Iran Plateau is higher in summer. Multiple sources of elements in deposited particles are identified. Calcium, iron, aluminum, and magnesium are mainly derived from remote regions, while zinc, copper and lead have predominantly anthropogenic sources. Atmospheric deposition can provide abundant nutrients to vegetation and consequently play a role in the succession of regional ecosystems by affecting the structure, function, diversity, and primary production of the vegetation, especially the exotic or short-lived opportunistic species in arid Asia. Nevertheless, there is not much evidence of the ecological effects of atmospheric deposition on the regional and local scale. The present results may help in further understanding the mechanism of atmospheric deposition as well as providing a motivation for the protection of the ecological environment in arid Asia.

1. Introduction

Arid Asia stretches from the Great Xing'an Mountains to the Caspian Sea, and has a land area of 1.3×10^7 km^2 and an annual mean precipitation of < 500 mm (Fig. 1). This region has the largest population (approximately 330 million people) among all the arid regions of the world. The soil types from north to south are Kastanozems, Calcisols, Arenosols and Cambisols (Food and Agriculture Organization Soil Classification; Deckers et al., 1998). Arid Asia has highly heterogeneous landscapes, including gravel desert (e.g., Ala Shan Gravel Desert), sand desert (e.g., Taklimakan Desert), desert steppe (e.g. Otindag Sandy Land), steppe (e.g., Golodnaya Steppe), and cultivated land (e.g., Indus River Plain). The soil is infertile, and the output and input of nutrients may profoundly affect the basic soil properties, thus the growth and succession of vegetation (Dong et al., 2000; Okin et al., 2004; Shen et al., 2016).

In arid areas, dry deposition which proceeds via the gravitational settling of particulates from the atmosphere and their turbulent mixing, is the main route of aerosol dust deposition (Tegen and Fung, 1994; Zhao et al., 2003). Arid Asia is one of the main source regions for global atmospheric aerosols and total suspended particulates (Ginoux et al., 2001; Zender et al., 2003; Kim et al., 2017), and approximately 30%–80% of the suspended particulates will redeposit in the source regions due to gravity (Zhang, 2001; Zhao et al., 2003; Chen et al., 2014). The deposition of particulates can alter the physical and chemical properties of soils, especially the cycling and status of nutrients in the surface soil (Reynolds et al., 2006; Rizzolo et al., 2017). For example, atmospheric deposits rich in various nutrients can remedy the loss of nutrients in surface soil by erosion, and consequently affect the growth and community structure of vegetation (Gillette and Dobrowolski, 1993; Li et al., 2009; Zhao et al., 2011; Yan et al., 2013). Previous studies have focused on the magnitude of dust emissions,

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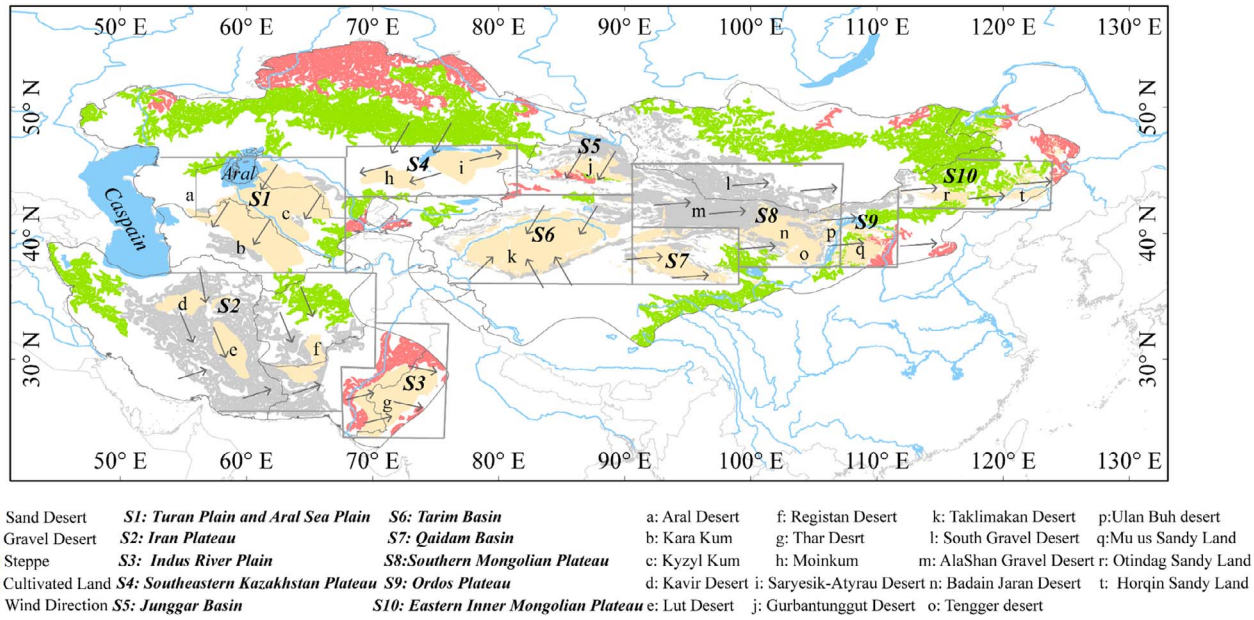

Fig. 1. Map of arid Asia and the main atmospheric deposition/dust aerosol source regions (Notes: S refers to the main dust deposition source; land cover classification is from GLCNMO: https://globalmaps.github.io/glcnmo.html and http://westdc.westgis.ac.cn/data/122c9ac2-53ee-4b9a-ae87-1a980b131c9b).

temporal and spatial variations in dust emissions, and the effects of dust emissions on human health and the environment in the distant dust source areas and ecosystems of arid Asia (Crouvi et al., 2010; Pullen et al., 2011; Martino et al., 2014; Aciego et al., 2017). There have been few reports on the deposition flux, regional variation, and the ecological effects of atmospheric deposition in arid Asia. Previous studies have mainly been focused on the local scale, including 1) the deposition flux (Zhang and Kang, 1999; Groll et al., 2013; Wang et al., 2013a); 2) the adverse environmental effects of atmospheric deposition, especially white and salt sandstorms and heavy-metal contamination (Orlovsky et al., 2005; Indoiu et al., 2012; Abdollahi et al., 2013); and 3) the different characteristics of atmospheric deposition according to special weather conditions (Li, 2008; Muhammad, 2009; Lyu et al., 2010). There has been no study of atmospheric deposition on a regional or larger scale in arid Asia. Therefore, this paper analyzed the temporal and spatial variations in atmospheric deposition and its ecological effects in arid Asia based on an intensive review of literature. This study aims to increase the understanding of the potential distribution characteristics of atmospheric deposition and its ecological effects in the arid Asia, as well as providing a motivation for the protection of the ecological environment in arid Asia.

2. Methods

2.1. Deposition flux of dustfall

Atmospheric dustfall refers to particulate matter in the air with an aerodynamic diameter of > 10 μm, which falls naturally to the ground surface under the force of gravity (Liu et al., 2004; Zhang et al., 2010). The deposition flux of dustfall is usually defined as the weight of settled particulate matter per unit area per month (Wang, 2003; Groll et al., 2013). Although the monitoring of dustfall is relatively simple, its measurement is subject to many external influences, including the physical properties (e.g., shape and materials) of the collector (Sanderson et al., 1963; Patel and Pandey, 1986), the sampling medium (Goossens and Offer, 1994; Qian and Dong, 2004), the place of the dustfall collector (McTainsh et al., 1997; Zhang and Dong, 2013), the sampling location (Evyatar and Tsoar, 1999; Liu et al., 2004), and meteorological conditions (Wiggs et al., 2003; Lyu et al., 2010). The raw data of deposition flux of dustfall cannot be directly compared due to the influences of the aforementioned factors. Therefore, standardization or calibration is essential to enable the comparison in deposition flux of dustfall obtained by various methods under different circumstances.

The most important factor which influences the deposition flux of dustfall is the sampling medium (McTainsh et al., 1997). The dustfall is usually collected by three methods: the dry method, the wet method, and the marbles method. The three methods differ in the treatment of the bottom of the collectors. Mediums at the bottom of the collectors are nothing (clean surface; dry method), free water or glycerol surface (wet method), or 1–2 layers of marbles (marbles method), respectively. It has been reported that the wet method collected the maximum dustfall, followed by the marbles method, and the dry method captured the least dustfall (Goossens and Offer, 1994; Hu, 2002; Zhang and Dong, 2013). Linear correlations have been observed among the three methods (Goossens and Offer, 1994; McTainsh et al., 1997; Hu, 2002; Wang, 2003; Qian and Dong, 2004; Zhang and Dong, 2013). In this study, the wet method is treated as the standard method, and linear regression equations are obtained are to calibrate the dry method and the marbles method (Fig. 2). To assess the goodness of fit of the linear regression equations, statistical indicators: the coefficient of determination (R^2), the mean absolute error (MAE) and root mean squared error (RMSE) are calculated as follows:

$$R^2 = \frac{\left(\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})\right)^2}{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(y_i-\bar{y})^2} \quad (1)$$

$$MAE = \frac{\sum_{i=1}^{n}|x_i-y_i|}{n} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i-y_i)^2}{n}} \quad (3)$$

where x_i refers to the deposition flux of the dry or marbles method, y_i refers to the deposition flux of the wet method, $\bar{x}$ refers to the mean deposition flux of the dry or marbles method, $\bar{y}$ refers to the mean deposition flux of the wet method, n refers to the number of data.

In this study, the unit of deposition flux is defined as g m^{-2} (the sum of deposition flux in 12 months for annual mean deposition flux, and the sum of deposition in 3 months for seasonal deposition flux, see Appendix A and B).

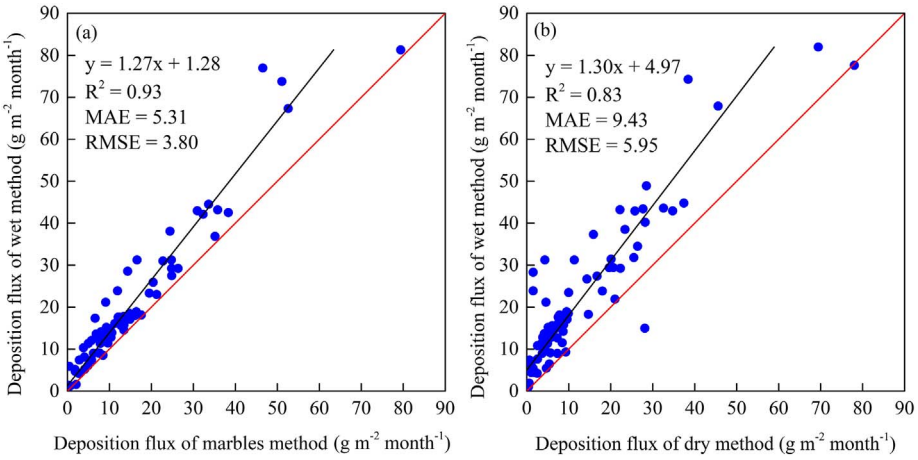
(a)
y = 1.27x + 1.28
R² = 0.93
MAE = 5.31
RMSE = 3.80
Deposition flux of wet method (g m⁻² month⁻¹)
Deposition flux of marbles method (g m⁻² month⁻¹)
(b)
y = 1.30x + 4.97
R² = 0.83
MAE = 9.43
RMSE = 5.95
Deposition flux of wet method (g m⁻² month⁻¹)
Deposition flux of dry method (g m⁻² month⁻¹)

Fig. 2. The relationship of the deposition flux of the wet method with those of marbles (a) and the dry method (b).

2.2. Elemental analysis of dustfall

Previous studies undertook chemical analyses using various methods, including X-ray fluorescence and inductively coupled plasma–mass spectrometry (Appendix C), but the concentrations of elements in the dustfall are comparable among the different methods and different pretreatments, as shown for analyses of heavy metals in soil and dustfall samples (Zhang et al., 2013; Zheng et al., 2017).

3. Spatial and seasonal variations in the flux of atmospheric deposition

3.1. Spatial variation in annual mean atmospheric deposition

The annual mean atmospheric deposition flux generally decreases from west to east in the study region, and regions with the highest flux are mainly located in the Aral Sea Desert (a), Taklimakan Desert (b), and Kyzyl Kum Desert (c), and their surrounding areas (Fig. 3). This trend is consistent with other results derived from empirical formulae and models (Zhang et al., 1997; Ginoux et al., 2001; Ginoux et al., 2012). The deposition flux is high on the Turan Plain and Aral Sea Plain (S1), including the Aral Sea Desert (a), Karakum Desert (b), and Kyzyl Kum Desert (c), where particulate matter in the atmosphere is enhanced because the areas of dry lakebeds in the Aral Sea or dry riverbeds have increased since water has been diverted due to increasing agricultural activities or other anthropogenic activities (Wake et al., 1994; Indoiu et al., 2012; Groll et al., 2013). However, the deposition fluxes are lower to the northeast and southwest of the Turan Plain and the Aral Sea Plain (S1), which are far from the dust source areas. These areas are characterized by lower deposition intensities and weaker correlations between dust deposition and air temperature or wind speed were observed (Semenov et al., 1990; Groll et al., 2013). The deposition fluxes range from 100 to 300 g m^{-2} in the Iran Plateau (S2) and Indus Plain (S3), and relatively higher deposition flux occurs in central Pakistan, which experiences severe dust events that originate in desert regions of Iran and Afghan (Sami et al., 2006).

The deposition flux is relatively low in the Junggar Basin (S5), where resistance to wind erosion is strong because of high vegetation coverage (Sun et al., 2001b) The Tarim Basin (S6) shows a high deposition flux, particularly in the southern section, under the anticyclonic northeastern wind in the eastern basin and the cyclonic northwest wind in the western basin, which control the main direction of wind (Liu et al., 1994; Wang et al., 2013a). Among the Qaidam Basin (S7), southern Mongolian Plateau (S8), Ordos Plateau (S9), and eastern Inner Mongolia Plateau (S10), the deposition fluxes are greatest on the southern Mongolian Plateau (S8) and Ordos Plateau (S9), which are surrounded by the Badain Jaran Desert (n), the Tengger Desert (o), the Ulan Buh Desert (p), and a large area of the grave desert (m and l; Sun, 2002). In the Qaidam Basin (S7), dust is emitted from the surrounding salt lakes, desert, and gravel desert. This region has the second largest deposition flux since most of the emitted dust is deposited during its transport by the high-altitude westerly circulation (Qiang et al., 2007). The deposition flux is the lowest on the eastern Inner Mongolian Plateau (S10) where the annual precipitation and vegetation coverage are both high (Zhang et al., 1997; Li et al., 2004).

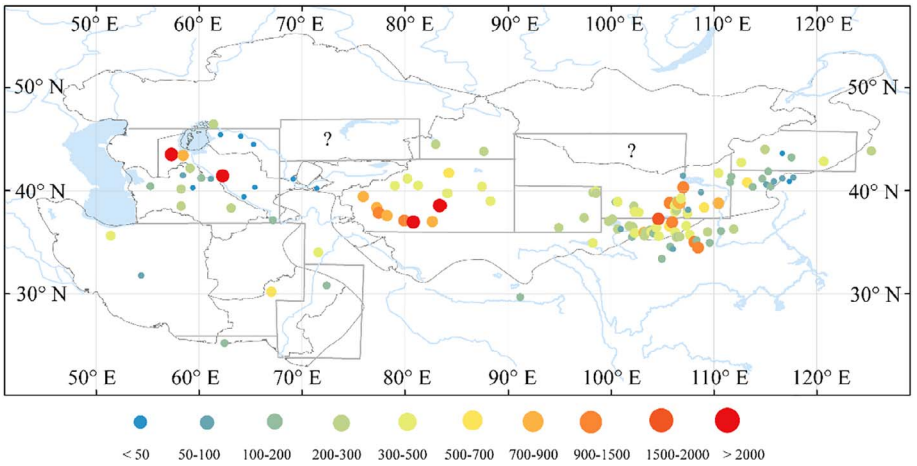

Fig. 3. Annual mean atmospheric deposition flux (g m^{-2}) (data from references: Imandel et al. (1981), Khan and Khan (1996), Wang et al. (1997, 2000, 2013, 2015), Zhang and Kang (1999), Sun et al. (2001a), Liu et al. (2004), Zhao et al. (2005), Nabizadeh et al. (2007), Abuduwaili et al. (2008), Li (2008), Muhammad (2009), Zhang et al. (2010, 2015b), Tang et al. (2011), Jia et al. (2012), Sami et al. (2012), Wan et al. (2012), Wang (2012a), Gao et al. (2013), Groll et al. (2013); ?: no data).

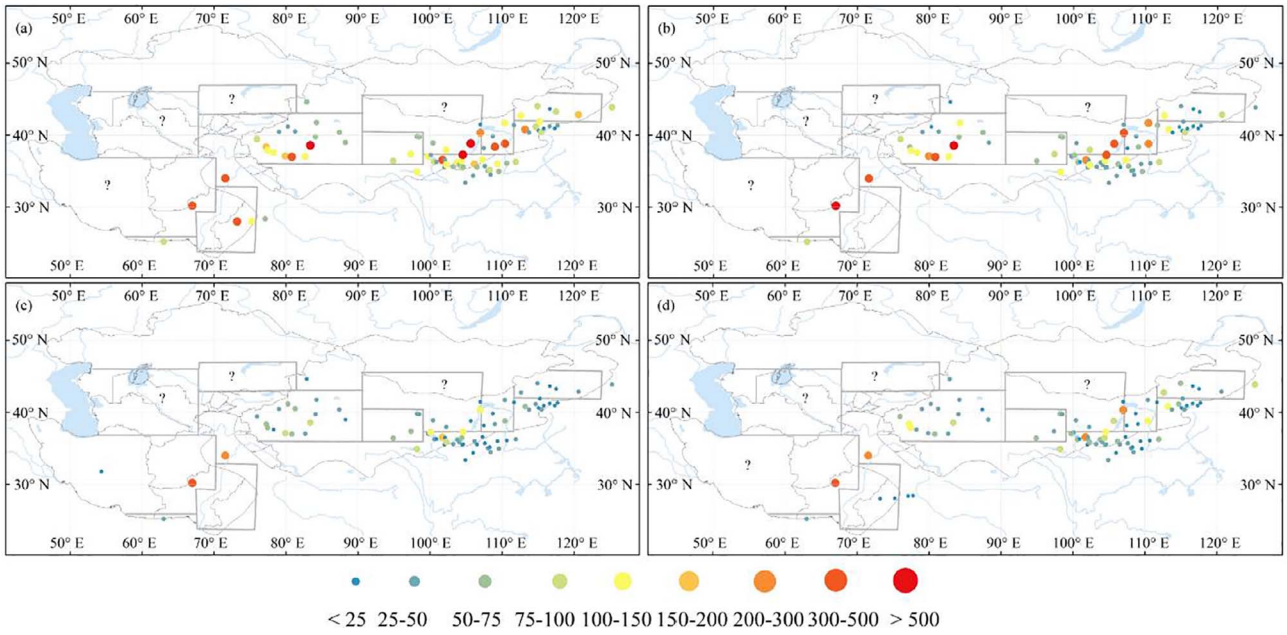

Fig. 4. Seasonal variation in the flux of atmospheric deposition ($g\,m^{-2}$) (data from references: Beg et al. (1991), Wang et al. (1997), Zhang and Kang (1999), Sun et al. (2001a), Khan et al. (2002), Liu et al. (2004)) Li (2008); Muhammad (2009), Tang et al. (2011), Jia et al. (2012), Wan et al. (2012), Wang (2012a), Gao et al. (2013), Zhang et al. (2015b); (a): Spring; (b): Summer; (c): Autumn; (d): Winter; ?: no data).

3.2. Spatial variation in seasonal mean atmospheric deposition

The deposition flux in arid Asia shows a pronounced seasonal trend, with the fluxes in spring and summer being generally greater than those in autumn and winter (Fig. 4). Summer and spring show the highest deposition fluxes of the four seasons in the western and eastern parts of arid Asia, respectively. The dark surface contributes to the heating of the western regions, which can stimulate the occurrence of a more intense aeolian transport of sand and dust (Orlovsky et al., 2005) and of more energetic cyclone activity and cold wave intrusion during summer (Létolle et al., 2005; Yadav and Rajamani, 2004). However, the greatest amount of deposition in spring in the eastern regions is attributed to the drought conditions, sparse vegetation, and frequent strong winds (Chen et al., 2011; Zhang et al., 2012a).

The deposition flux in spring is relatively high in various regions of arid Asia (Fig. 4a). On the Iran Plateau (S2) and the Indus Plain (S3), the deposition fluxes of the Thar Desert (g) and surrounding areas are higher under the influence of the strong westerly winds from Central Asia and West Asia and the hot dry climate (Sami et al., 2006; Shahsavani et al., 2012). In the Tarim Basin (S6), the deposition flux is highest in the south because of strong sandstorm activity and the predominance of northerly winds in spring (Liu et al., 1994; Zhang et al., 2015a). The spring deposition flux in the Qaidam Basin (S7) is much higher in the eastern section than in the central section because of the prevalence of westerly winds (Qiang et al., 2007). On the southern Mongolian Plateau (S8) and Ordos Plateau (S9), the spring deposition fluxes are higher because the surface is rich in particulate matter, and these regions experience a high frequency of dust storms arising from the Mongolian high pressure system (Guo et al., 2011; Zhang et al., 2012b). On the eastern Inner Mongolian Plateau (S10), the deposition flux is relatively low, except in the Otindag Sandy Land (r) and Horqin Sandy Land (t), where lower vegetation coverage and severe desertification contribute to dust emission (Li et al., 2004).

The deposition flux in arid Asia is also high in summer (Fig. 4b). On the Iran Plateau (S2) and in the Tarim Basin (S6), the deposition flux is highest in summer, which is a hot and windy period with low precipitation, due to the northward movement of the subtropical high and the prevailing westerlies (Liu et al., 1994; Shen et al., 2016). In the Qaidam Basin (S7), the spatial differences in the deposition flux between different sections are smaller in summer than in spring. Because of the influence of the summer monsoon, the region is prone to windy weather that has a narrower scope of influence in summer than in spring (Zhang et al., 2014a). On the southern Mongolian Plateau (S8) and Ordos Plateau (S9), higher deposition fluxes in summer are only observed in the Badain Jaran Desert (m), Tengger Desert (o), Ulan Buh Desert (p), and Mu Us Sandy Land (q), because the number of gale days (the day that the maximum instantaneous wind speed is more than $17.2\,m\,s^{-1}$ or the wind power is over category 8 (fresh gale) is defined as gale day) generally decreases and the precipitation increases in summer (Yao et al., 2006). With the lower wind speed and increased vegetation cover on the eastern Inner Mongolian Plateau (S10), the deposition flux in the surrounding sandy land declines sharply, and the difference in the deposition flux between the sandy land and grassland decreases (Liu et al., 1994; Zhang et al., 2012b).

In autumn, the pattern of deposition flux varies across the Iran Plateau (S2), and the northeastern section experiences the greatest deposition. This may be attributed to the location of the dust source areas in the northeastern part of the plateau, and the lower wind speed in autumn, which reduces the transport of dust plumes from dust source areas to other locations (Nabavi et al., 2016). Because the northerly wind speed in the Tarim Basin (S6) decreases (Zhang et al., 2015a), the variation in the deposition flux is smaller. However, the deposition flux remains higher in the southern section than the northern section. The deposition fluxes are low in the Qaidam Basin (S7) and on the southern Mongolian Plateau (S8), the Ordos Plateau (S9), and the eastern Inner Mongolian Plateau (S10) in autumn. This may be related to the increased precipitation which may increase water content of topsoil to reduce the emission of dust particles and remove fine particles suspended in the atmosphere, the stable atmospheric structure, and the lower wind speed (Li, 2008).

In winter, the deposition flux is also geographically heterogeneous on the Iran Plateau (S2), with a higher flux in the northeastern region (Nabavi et al., 2016). On the Indus Plain (S3), where dust storms are less likely to form because precipitation is heavier due to the influence of the Qinghai–Tibet Plateau, the deposition flux is low and displays small spatial differences (Yadav and Rajamani, 2004). In the Tarim Basin (S6), the spatial distribution of the deposition flux in winter is similar to that in autumn. In the Qaidam Basin (S7) and on the southern

Mongolian Plateau (S8), the Ordos Plateau (S9) and the eastern Inner Mongolian Plateau (S10), the highest deposition flux is in the deserts and their surrounding areas. The deposition flux is lower in other regions, where the temperatures are low and snow or frost forms under the influence of the prevailing northwesterly wind, which is affected by the polar high pressure in winter (Li, 2008).

4. Spatial variation in the composition of atmospheric deposition

The elements in the atmospheric deposition show distinct regional differences (Appendix C and D), which may be related to differences in the dust sources. Atmospheric deposition is affected by both anthropogenic activity and natural factors (Wu et al., 2015; Zhang et al., 2017). Arid Asia is one of the main dust emission and deposition regions in the world (Ginoux et al., 2001; Shao et al., 2002; Lee et al., 2006; Shao et al., 2011), natural factors such as climate changes, land degradation, extreme weather, and anthropogenic activities, such as mining, fossil fuel burning, and industry activities, contribute to the spatial differences in the compositions of atmospheric deposition. The zinc (Zn) contents of the dustfall are higher in the northeastern section of the Iran Plateau (S2), the southern Junggar Basin (S5), the Tarim Basin (S6), and the southern Mongolian Plateau (S8) than in other regions (Fig. 5a). The copper (Cu; Fig. 5b) contents are higher in the northern Junggar Basin (S5) and southern sections of the Mongolian Plateau (S8) and Ordos Plateau (S9) than in other regions. The lead (Pb; Fig. 5c) contents are highest in the eastern Iran Plateau (S2) and Indus Plain (S3), followed by the eastern Qaidam Basin (S7), whereas the Pb contents in the remaining regions are low. The nickel (Ni; Fig. 5d) contents are highest in the eastern Iran Plateau (S2) and northern Indus Plain (S3), followed by the southern Junggar Basin (S5), the southern Mongolian Plateau (S8), and the southern Ordos Plateau (S9), whereas the Ni contents in the remaining regions are low. The manganese (Mn; Fig. 5e) contents are highest in the eastern Qaidam Basin (S7) and the southern Mongolian Plateau (S8), followed by the southern Iran Plateau (S2), southern Tarim Basin (S6), northern Ordos Plateau (S9) and southern Inner Mongolian Plateau (S10), whereas the Mn contents in the remaining regions are low. The chromium (Cr; Fig. 5f) contents in the Tarim Basin (S6) and eastern Inner Mongolian Plateau (S10) are relatively low.

Most areas of arid Asia are classified as arid or semiarid, where dust events occur frequently in spring and summer, and the suspended particulate matter is widely deposited geographically. Arid Asia is also the most densely populated arid region in the world. Therefore, the composition of the atmospheric deposition in arid Asia is affected by both the composition of the surface materials and local human activity (Carmichael et al., 2009; Wang et al., 2010). In general, the concentrations of all the elements at each site varies substantially. Crustal elements, such as calcium (Ca), iron (Fe), aluminum (Al), and magnesium (Mg), are the most abundant elements in the atmospheric deposition (Appendix C). In the Tengger Desert, the proportion of Ca, Fe, Al and Mg in the dustfall is 1.25%, 3.06%, 8.16%, 0.98%, respectively (Zhang and Dong, 2014). In the Hotan region, the proportion of Ca, Fe,

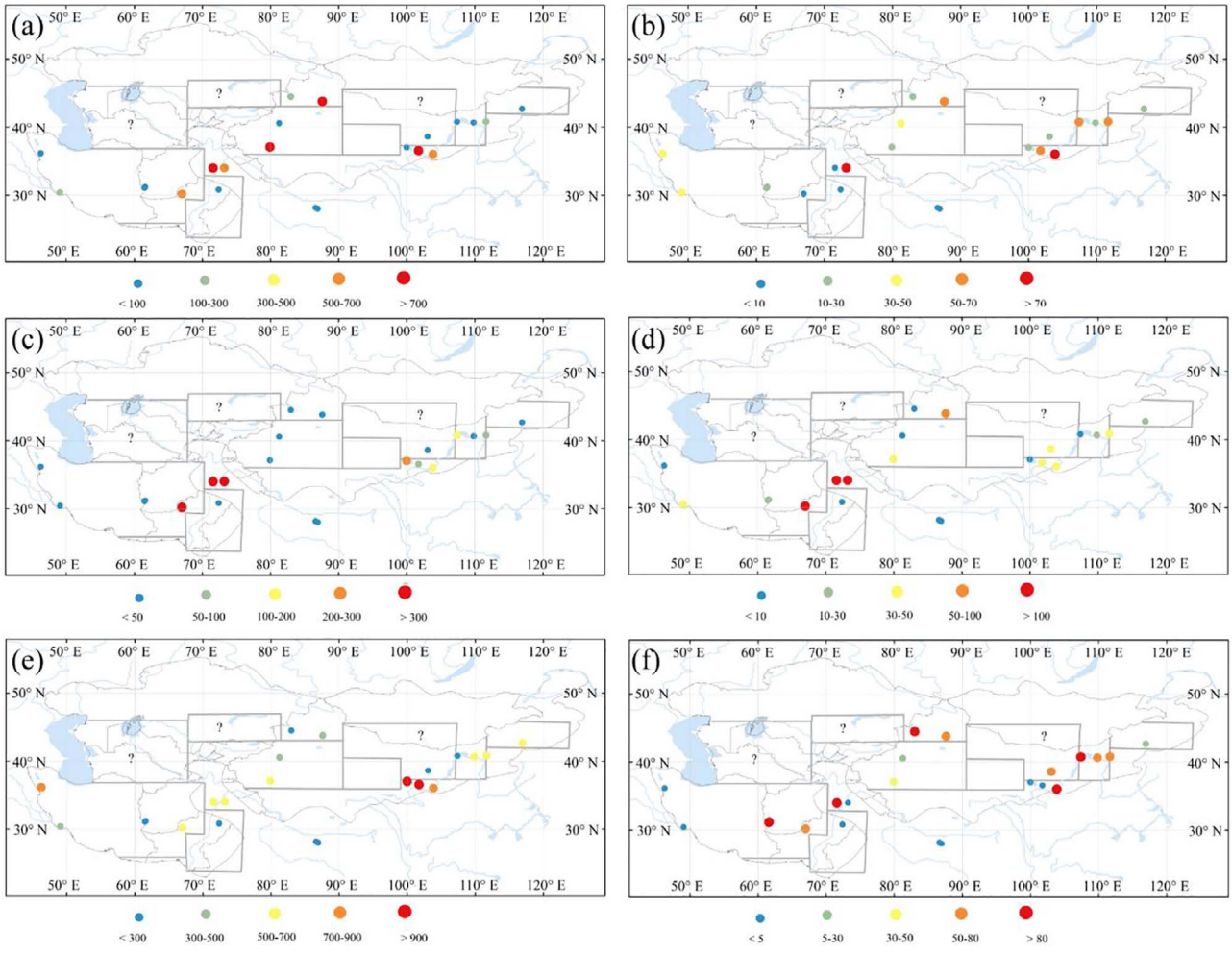

Fig. 5. The spatial distribution of the concentration of some elements in atmospheric deposition (mg kg^{-1}) (Notes: a refers to Zn; b refers to Cu; c refers to Pb; d refers to Ni; e refers to Mn; f refers to Cr).

Table 1
The content of soil and dust elements in different regions of arid Asia.

Region	Type	Al	Fe	Mn	Cu	Zn	Pb	Ni	Cr	References
a10	Soil	–	–	142.3	38.5	42.6	11.4	–	–	Hussain (2001)
	AD	–	–	533.0	283.0	931.0	446.0	–	–	Hussain (2001)
a13	Soil	–	0.3	688.0	26.7	68.8	3.0	26.6	49.3	CNEMC (1990)
	AD	–	7.9	404.6	56.5	722.9	34.6	48.5	6.4	Wei et al. (2015)
a15	Soil	–	–	–	13.0	152.9	–	19.6	22.8	Wen (2001)
	AD	–	23.6	549.5	16.6	505.3	–	45.9	37.2	Li (2012)
a18	Soil	–	21.4	505.4	21.9	55.7	21.7	13.2	63.9	Lu et al. (1987)
	AD	–	52.3	825.7	72.7	520.1	135.9	38.6	80.7	Yang et al. (2002)
a21	Soil	107.5	3.9	973.4	20.7	113.0	38.3	25.5	63.7	Xu et al. (2011)
	AD	106.1	70.2	593.6	23.1	87.2	33.1	22.9	65.4	Wang (2012b)
a23	Soil	–	–	320.0	9.5	–	12.5	12.5	29.6	Liu et al. (2016b)
	AD	–	–	538.0	19.7	–	38.3	18.4	29.7	Qiao et al. (2013)

Notes: the unit of Al and Fe element: g kg^{-1}; the unit of other elements: mg kg^{-1}; AD: atmospheric deposition (dustfall); the location of Region is from Appendix D. CNEMC is reference to China National Environmental Monitoring Center.

Al and Mg in the dustfall is 5.6%, 3.6%, 9.3%, and 0.21%, respectively (Wen, 2001). These results indicate that wind-driven crustal materials comprise a large proportion of the atmospheric deposition. With increases in human activity, such as fossil fuel combustion and increases in building dust and other types of particles, several elements, particularly metals (such as Cu, Pb, and Zn), are enriched in the atmospheric particulates deposited (Li et al., 1997; Eqani et al., 2016). Although the concentrations of metal elements are low (Wang et al., 2010; Zhang and Dong, 2013), metals have significant residence times in the soil before they enter the atmosphere via erosion and are transported to downwind regions and deposited (Galloway et al., 1982; Johnson et al., 1994). The metal elements in the atmospheric deposition are a complex mixture that originate from both natural and anthropogenic sources. Among the elements (Zn, Cu, Pb, Ni, Mn, and Cr), the Zn, Cu and Pb are derived mainly from anthropogenic sources, and Ni, Mn and Cr from natural sources (Ding et al., 2001; Castillo et al., 2008; Wang et al., 2010). Differences in the geography, population densities, and industrial structures in arid Asia have a remarkable effect on the regional differentiation of specific elements such as the Zn, Cu and Pb in dust. The concentrations of other elements such as Ni, Mn and Cr are influenced mainly by the distance from dust source areas and the dry meteorological conditions, which favor dust emissions. In the eastern Inner Mongolian Plateau (S10), the mean concentrations of Pb, Zn, and Cu are higher in Hebei and Beijing while the lowest are in Inner Mongolia. The sampling sites of Inner Mongolia are defined as unpolluted region whereas the sampling sites of Hebei and Beijing are characterized by moderate pollution (Qiao et al., 2013). The concentrations of heavy metal elements in dustfall are higher in the industrial or urban centers than remote region in this study region, because these elements are mainly contaminated by local anthropogenic activity.

5. Ecological and environmental effects of atmospheric deposition

5.1. The potential effect of atmospheric deposition on soil

Atmospheric deposition plays a crucial role in determining soil nutrients, moisture, and the formation of soil biological crust (McTainsh, 1984; Kohfeld and Harrison, 2001; Reynolds et al., 2001; McTainsh and Strong, 2007). In arid Asia, the soil is mainly alkaline, with low fertility and a low clay fraction (Appendix E). The emission and deposition of dust may alter the contents of fine particles and elements, and consequently, the texture, structure, and water retention of the topsoil. These changes may have a major effect on regional ecosystems by affecting the growth and succession of the vegetation. Atmospheric deposition can provide fine-fraction particles to the topsoil (Simonson, 1995; Shen et al., 2016), supply organic matter and nutrients (Okin et al., 2004; Li et al., 2009), and adjust the soil pH with the deposition of water-soluble salts (McTainsh and Strong, 2007; Shen et al., 2016). Most studies have focused on the impact of atmospheric deposition on the heterogeneity of soil nutrients. However, particulate matter (mainly silt fraction) from the atmosphere fills the soil pores, changes the soil texture, promotes the granular structure of the soil, and thus improves its water-holding capacity (Duan et al., 2003; Su et al., 2009). Furthermore, because particulate matter is rich in organic matter and nutrients, atmospheric deposition also changes the soil nutrient status and promotes the formation of the soil biological crust (Gillette and Dobrowolski, 1993; Zhao et al., 2011). In arid Asia, the particulate matter in atmospheric deposition contains abundant nutrients. For example, in the Hotan region of the Tarim Basin (S6), the proportion of fine particulate matter, organic matter and available nitrogen (N), phosphorus (P), and potassium (K) increase in the soil columns that received atmospheric deposition (Wen, 2001). On the western Loess Plateau, significantly more dust accumulates on gravel-covered substratum than on gravel-free substratum, and the gravel cover and pebble size have different effects on the accumulation of aeolian dust. Moreover, the N and organic matter contents of the dust are 2–3 times higher than those of the local soil, suggesting that dust accumulation supplied nutrients to the gravel-mulched fields (Li and Liu, 2003). On the semiarid steppe of the Xinlin River Basin (Inner Mongolia, China), the vegetation coverage significantly affects dust accumulation, and the total accumulation reaches a maximum coverage of 75% and remains stable with further increases in vegetation coverage. The dust trapped by different vegetation covers also has higher contents of organic carbon, N, and P (Yan et al., 2011).

Particles from different source regions supply the surface soil with a variety of nutrient elements, particularly trace elements, and the output and input of fine particles changes the chemical properties of the soil and improves soil fertility (Table 1; Appendix D). In the Abbottabad region (a10), atmospheric deposition provides a relatively rich abundance of Zn, Mn, Cu and Pb to the soil, which is lacking in those elements. In the Urumqi region (a13), the soil is relatively rich in Fe, Cu, Zn, Pb, and Ni as a result of atmospheric deposition. The atmospheric deposition in the Hotan region (a15) is relatively rich in Zn, Cr, and Ni, and it supplements the soil with these elements. In the Lanzhou region (a18), although the atmospheric deposition is relatively rich in Fe, the soil contains mainly Mn and Cu. In the Baotou region (a21), the atmospheric deposition is relatively rich in Fe, which makes the regional soil also relatively rich in Fe. In the Duolun region (a23), atmospheric deposition makes the soil relatively rich in metals.

5.2. Potential impact of atmospheric deposition on vegetation

Atmospheric deposition can provide a variety of macronutrients and trace elements, and it is an important source of nutrients for the vegetation of arid Asia. The composition and amount of deposited particles show marked spatial variations, meaning that atmospheric

Table 2
Enrichment of heavy metal in the vegetation of arid regions.

Vegetation	Region	Element enrichment	References
Collema tenax (Sw.) Ach. em. Degel.	b1	Mn	Bowker et al. (2005)
Pteridium scopoli.	b2	Zn, Cd	Sánchez-López et al. (2015)
Gnaphalium affine D. Don	b2	Cu	Sánchez-López et al. (2015)
Ceratodon purpureus (Hedw.) Bird.	b3	Zn, Cr, Pb	Spencer (2001)
Festuca ovina L.	b4	Fe, Cu	Alvarez et al. (2003)
Zygophyllum fabago L.	b5	Zn	Conesa et al. (2006)
Tamarix chinensis Lour.	b5	Cu	Conesa et al. (2006)
Festuuca pratensis Huds.	b6	Sn	Elekes et al. (2010)
Trianthema portulacastrum L.	b8	Cu, Zn, Fe	Hussain et al. (2010)
Gynandriris sisyrinchium Parl.	b7	Al, Fe,V	Bu-Olayan and Thomas (2009)
Amaranthus viridus L.	b9	Na, Ni	Hussain and Durrani (2009)
Chenopodium album L.	b9	Co, Fe	Hussain and Durrani (2009)
Karelinia caspica (Pall.) Less.	b10	Cd, Zn	Liu et al. (2016a)
Scorzonera pusilla Pall.	b11	Fe	Qian et al. (2015)
Ferula dubjanskyi Korov. ex Pavl.	b11	Fe	Qian et al. (2015)
Gagea divaricata Regel.	b11	Fe	Qian et al. (2015)
Gentiana dahurica Fisch. var. dahurica	b12	Cu	Li (2013)
Puccinellia tenuiflora (Griseb.) Scribn.	b12	Cu	Li (2013)
Ajania khartensis (Jacq.) Tzvel.	b12	Cu	Li (2013)
Iris Iactea Pall. var. chinensis (Fisch.) Koidz.	b12	Sr	Li (2013)
Polygonum sibiricum Laxm.	b12	Pb	Li (2013)
Haloxylon ammodendron (C. A. Mey.) Bunge	b13	Na	Wang et al. (2004)
Ceratoides lateens (J. F. Gmel.) Reveal et Holmgren	b14	Ni, Cu	Gong (2013)
Caragana Korshinskii Kom.	b14	Ni, Cu	Gong (2013)
Caragana Korshinskii Kom.	b15	Ca, K, Al	Liu et al. (2008)

Notes: the location of region is shown in Appendix F.

deposition might affect the spatial distribution of vegetation.

The growth of different plant species is limited by different macro elements in arid Asia. In Mu Us Sandy Land, the growth of plants such as *Artemisia ordosica* Krasch., *Hedysarum mongolicum* Turcz., *Thermopsis lanceolata* R. Br., and *Leymus secalinus* (Georgi) Tzvel. is strongly dependent on phosphorus (P; Zhang et al., 2016). In eastern Mongolia, the growth of *Leymus chinensis* (Georgi) Tzvel. and *Cleistogenes chinensis* (Maxim.) Keng. is restricted by the availability of calcium (Ca), magnesium (Mg) and sodium(Na; Olson et al., 2010). In the Horqin Sandy Land, the growth of *Artemisia scoparia* Waldst. et Kit. and *Pennisetum flaccidum* Tzvel. is mainly limited by nitrogen (N), whereas the growth of *Caragana microphylla* Lam. is restricted by organic carbon, total N, total P, and available K (Zuo et al., 2007; Jiang, 2010).

The enrichment degree of metal elements in the vegetation shows marked variations, which may affect the spatial distribution of vegetation. Metal toxicity has a strong effect on and relevance to plants, and consequently affects the ecosystems. There have been few reports of the response of vegetation to metal elements in arid Asia (Table 2; Appendix F). Plants growing in metal-polluted sites showed altered metabolism, growth reduction, lower biomass production, and metal accumulation (Blaylock and Huang 2000; Monni et al.2000; Tamás et al., 2009; Hu et al., 2013). The low concentration of Ni (10 μmol L^{-1}) does not significantly inhibit *Thinopyrum ponticum*, but as the Ni concentration increases, the plant's growth parameters decrease significantly, and the damage to its roots is severe. However, Ni has a stronger inhibitory effect on the seed germination of *Corispermum*, irrespective of its concentration (Lu et al., 2009). Treatment with low-concentration cadmium (Cd) promotes the aboveground biomass of perennial ryegrass, white clover, and Kentucky bluegrass, but as the ion concentration increased, the aboveground biomass decreases. Under Pb stress, the aboveground biomass of those plants decreases significantly, irrespective of the concentration (Chen, 2014). Various physiological and biochemical processes in plants are also affected by metals (Nagajyoti et al., 2010). Some heavy metals are essential for plants, and Cu, Zn, Fe, Mn, molybdenum (Mo), Ni and cobalt (Co) are essential micronutrients (Reeves and Baker, 2000; Wintz et al., 2002) that play biochemical and physiological roles in plants, including in redox reactions and as integral cofactors of several enzymes. However, excessive Zn can give rise to Mn and Cu deficiencies in plant shoots, and the Cu and Mn concentrations in plants grown in Zn-rich media are greater in the roots than in the shoots (Ebbs and Kochian, 1997). Another typical effect of Zn toxicity is the appearance of a purplish-red color in the leaves, which is ascribed to P deficiency (Lee et al., 1996). The high uptake of Ni induces a decline in the water content of dicot and monocot plant species, and reduced water uptake is an indicator of the progression of Ni toxicity in plants (Pandey and Sharma, 2002; Gajewska et al., 2006). In Cd-treated plants, Ca content usually decreases, whereas the K content appears to increase (Smith and Brennan, 1984; Peachey et al., 2009). Heavy-metal toxicity in plants varies with the plant species, the specific metal, its concentration, and chemical form, soil composition and soil pH (Malik et al., 2010; Gill, 2014). In arid Asia, deposited particles that contain various heavy metals may have no significant toxic effects on some plants, have adapted to the polluted environments over time.

Arid Asia is also a region with high frequencies of dust and salt storms (Zhang et al., 2003; Orlovsky et al., 2005; Wang et al., 2012). This vast region is characterized by deserts, ephemeral rivers and streams, alluvial fans, playas, and saline lakes, and represents a main source area for minerals and salts on the Asian continent (Prospero et al., 2002; Indoiu et al., 2012). In the Ebinur region, the amount of salts deposited with dust usually ranges from 14 $g\,m^{-2}\,yr^{-1}$ to 27 $g\,m^{-2}\,yr^{-1}$ and the recorded maximum amount is 77 $g\,m^{-2}\,yr^{-1}$ (Abuduwaili et al., 2012). With the expansion of irrigated agricultural land in the Aral Basin, the newly dried bottom of the Aral Sea is a large source of dust and salt aerosols (Orlovsky and Orlovsky, 2002; Galaeva and Idrysova, 2007). The amount of depositional material from the exposed bottom of the Aral Sea is approximately 150 $g\,m^{-2}\,yr^{-1}$ (Singer et al., 2003). Saline dust storms not only contribute to soil salinization, but also seriously affect vegetation. The impact of moving particles abrades plant leaves and stems (Armbrust, 1984; Armbrust and Paulsen, 1973), and may damage the structure of leaf cells and reduce chlorophyll content in leaves (Genis et al., 2013). Salt can also form a fine surface layer that absorbs plant water and blocks stomatal opening, thus affects respiration and photosynthesis, and ultimately damages the plants (Hirano et al., 1995; Darley, 1996; Burkhardt et al. 1999). The salts in aeolian deposited particles include some harmful

chemicals, such as sodium bicarbonate ($NaHCO_3$), sodium chloride (NaCl), and sodium sulfate (Na_2SO_4; Micklin, 2010). Under salt stress, the capacity of plants to absorb Na can increase greatly, whereas their capacity for K absorption is greatly reduced (Tuerhong et al., 2009; Shaheen et al., 2016). Salts can destroy the dynamic balance of ions in plants and block the plants' capacity to absorb mineral nutrients. Therefore, salt dust deposited on vegetation can reduce the biomass and productivity because the plant must spend more energy to extract water and to survive under stressed conditions. The degree of salts' effects on vegetation is dependent on the stage of plant growth and on the tolerance of individual plants to salt. For example, the effects of salts on native desert plants like alhagaparsi folia (*Alhagi sparsifolia* Shap.) and wolfberry (*Lycium chinense* Mill.) are negligible, whereas once oil sunflower (*Helianthus annuus* L.) and corn (*Zea mays* L.) are contaminated with salt dust, their leaves immediately wither and turn yellow (Rhoades and Goudie, 1990).

Nitrogen and phosphorus are the key nutrients that limit vegetation growth and productivity, as well as other ecological processes in terrestrial ecosystems (Elser et al., 2007; Vitousek et al., 2010). In the future, the annual increased deposition flux exceeds $1\,g\,N\,m^{-2}\,yr^{-1}$ and the deposition flux of arid regions is going to increase proportionally (Lamarque et al., 2005). For example, the annual nitrogen deposition flux of the Mojave Desert is approximately $3.2\,g\,N\,m^{-2}\,yr^{-1}$ that are comparable to the deposition flux of urban (Brooks, 2003). Previous researchers have focused mainly on the responses of the vegetation biomass and ecosystem structure to the addition of N and P (Okin et al., 2004; Stevens et al., 2004; Vitousek et al., 2010). The sensitivity of different vegetation types to the addition of N and P differs in different regions. In the Hulun Buir grassland, the addition of N alone, and N and P simultaneously results in a significant increase in the aboveground biomass of *Potentilla tanacetifolia* Willd. ex Schlecht, whereas the addition of P alone has little effect on biomass (Yang, 2016). In the Horqin sandy grassland, the addition of N increases the aboveground biomass of the vegetation (Zeng et al., 2010). In the temperate grassland of Inner Mongolia, the addition of N and P significantly increases the vegetation coverage and the aboveground biomass of *Composite* (He et al., 2015). At the southeastern margin of the Inner Mongolian Plateau, the addition of N increases the aboveground biomass to a different degree depending on the extent of grassland degradation, which conferred different N saturation thresholds on the grasslands (Xu et al., 2015). In typical grasslands of Inner Mongolia, the addition of N and P increases the aboveground biomass of *Leymus chinensis* Mill., and the underground biomass initially increases and then decreases (Zhan, 2015). In the subalpine meadows of the northeastern Qinghai–Tibet Plateau, the addition of N and P significantly increases the *Gramineous* plant biomass but has no significant effect on the biomass of *Cyperaceae* or weeds (Xin, 2011). Similarly, the effects of additions of N and P on vegetation diversity and the community structure of ecosystems also vary (Bardgett et al., 1999; Song et al., 2012; Zhao et al., 2014). Increases in N and P induce the disappearance of native or rare species in ecosystems (Lan and Bai, 2012; Su et al., 2013), and therefore reduce the vegetation diversity and disturb the stability and balance of ecosystems. In the Horqin sandy grassland, the addition of N changes the composition and diversity of the vegetation species, and C_4 perennials are replaced by C_3 annuals (Zeng et al., 2010). In the Xinlin River Basin, China, the addition of N reduces the species diversity, increases the annual plants, and reduces the perennial grasslands and shrubs (Bai et al., 2010). In the Duolun grassland of Inner Mongolia, N addition has no a significant effect on vegetation diversity (Xu et al., 2012). In the arid grassland of Xinjiang, the addition of N or P alone increases the diversity of the vegetation, whereas the simultaneous addition of N and P reduced the vegetation diversity (Zhao et al., 2013). In the subalpine meadows of the northeastern Qinghai–Tibet Plateau, the simultaneous addition of N and P changes the dominant species, and reduces species diversity (Shi et al., 2014).

Ecosystems in arid Asia always had a lack of nutrients (Xia and Wan, 2008). A number of researchers have reported similar effects of increased atmospheric deposition on various terrestrial biomes (Zavaleta et al., 2003; Clark and Tilman, 2008; Simkin et al., 2016). Arid and semiarid climates and low nutrients have nurtured the sensitive and fragile ecosystems in arid Asia. It is reported that the simultaneous addition of nutrients and water can significantly increase the vegetation coverage (Xi and Wan, 2008). In desert steppes, the addition of N increased the aboveground biomass in relatively wet years and reduced it in relatively dry years, while reducing the biodiversity in both wet and dry years (Su et al., 2013; Xu et al., 2015). The atmospheric deposition supplies the nutrients to the soil and vegetation, which affects the properties of soil and community structure. However, the input of nutrients companied with atmospheric deposition is a slow and steady process. Previous studies show that a slow, steady input enhances soil nutrients more effectively than pulsed inputs (Johnson, 1992; Hu et al., 2014). Atmospheric deposition affects vegetation indirectly by changing the soil chemistry. Its indirect effects via the soil are usually most significant because they positively affect plant growth, providing nutrients, neutralizing the pH, and reducing the availability of phytotoxic aluminum. The atmospheric input of nutrients into ecosystems can increase the growth of some plants, and alter competitive relationships, species compositions, and the diversity of ecosystems.

6. Conclusions

There are pronounced regional differences in atmospheric deposition within arid Asia during the contemporary period. The annual deposition flux decreases from west to east, and the annual deposition flux is higher on the Turan Plain, Aral Sea Desert and Tarim Basin than in other regions. There are also seasonal variations in the deposition flux. The Tarim Basin shows higher deposition flux in both spring and summer, the southern Mongolian Plateau has higher deposition flux in spring, and the deposition flux on the Iran Plateau is higher in summer. The spatial distribution of deposited particles has a dramatic effect on the growth of individual plants, plant community structures, and species diversity of the vegetation. The deposition of particulates provides fine-grained particles and abundant nutrients that can change the soil texture and improve soil fertility. Simultaneously, nutrient elements have a major influence on vegetation growth and ecosystems, as follows: 1) the deposition flux and the composition of particulates affect the spatial distribution patterns of vegetation; and 2) the deposited particulates, which are rich in nutrients such as N and P, can improve the aboveground biomass and reduce the species richness, further altering the stable structures and diversity of ecosystems in most areas of arid Asia.

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Appendix A. The sites of annual mean atmospheric deposition in different regions

Site	Lon. (° E)	Lat. (° N)	Dustfall	Calibration Dustfall	Collection methods	Collectors	Monitoring period	References
Tehran	51.39	35.64	215.72	285.13	Dry	Polyethylene bowl	1973.1–1974.12	Imandel et al. (1981)
Yazd	54.36	31.80	77.88	77.88	Wet	Cylindrical containers	2005.8–2006.4	Nabizadeh et al. (2007)
Chagyl	55.25	40.43	90.24	115.51	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Jasliq	57.31	43.53	2466.12	3122.95	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Bokurdak	58.24	38.51	204.72	260.42	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Darvaza	58.24	40.15	171.12	217.89	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Shasenem	58.43	41.50	61.68	79.35	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Mynak	58.44	43.45	537.00	681.03	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Kunya-Urgench	59.10	42.19	154.92	197.38	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Takhiatash	59.37	40.29	32.04	41.84	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Khiva	60.21	41.22	90.24	115.51	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Karachi	62.97	25.26	165.63	165.63	Wet	Cylindrical plastic container	1997–2002	Muhammad (2009)
Yangibazar	61.13	41.17	53.76	69.33	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Arakskoe	61.40	46.47	162.48	206.95	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Kazalinsk	62.07	45.46	21.72	28.77	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Bozaubay	62.28	41.45	8364.96	10589.84	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Repetek	63.10	38.33	213.96	272.11	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Dzhusaly	64.05	45.31	10.44	14.49	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Bukhara	64.37	39.43	4.32	6.75	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Kyzyl-Orda	65.30	44.51	31.44	41.08	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Nurata	65.41	40.33	7.68	11.00	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Quetta	67.00	30.20	510.76	510.76	Wet	Cylindrical plastic container	1997–2002	Muhammad (2009)
Termez	67.16	37.14	110.76	141.48	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Tashkent	69.16	41.16	10.68	14.80	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Ferghana	71.45	40.22	1.44	3.10	Marbles	Plastic tray	2003–2010	Groll et al. (2013)
Peshawar	71.58	34.02	316.88	316.88	Wet	Cylindrical plastic container	1997–2002	Muhammad (2009)
Islamabad	72.40	30.82	120.00	120.00	Wet	Cylindrical plastic container	–	Khan and Khan (1996)
Kashgar	75.97	39.44	708.67	708.67	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Yarkent	77.26	38.38	890.70	890.70	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Yecheng	77.44	37.88	1065.16	1065.16	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Pishan	78.28	37.60	785.56	785.56	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Kalpin	79.03	40.47	359.81	359.81	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Hotan	79.93	37.11	1405.16	1405.16	Wet	Cylindrical glass	2000–2012	Zhang et al. (2015a)
Asku	80.26	41.17	369.81	369.81	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Cele	80.82	36.99	2408.26	2408.26	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Alar	81.28	40.51	404.87	404.87	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Minfeng	82.68	37.04	815.21	815.21	Wet	Cylindrical glass	2007–2010	Wang et al. (2013)
Lake Ebinur	83.00	44.50	207.51	274.47	Dry	Metal bucket collector	1998.3–1999.4	Abuduwaili et al. (2008)
Tazhong	83.39	38.58	3772.81	3772.81	Wet	Cylindrical glass	2007–2010	Wang et al. (2013a,b)
Bachu	84.10	39.75	484.55	484.55	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Luntai	84.24	41.74	657.91	657.91	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Tieganlik	87.42	40.39	496.77	496.77	Wet	Cylindrical glass	2007–2010	Wang et al. (2013)
Urumqi	87.62	43.82	284.50	284.50	Wet	Cylindric glass vessels	1981–2004	Zhang et al. (2010)
Ruoqiang	88.26	38.99	428.07	428.07	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Lhasa	91.15	29.69	177.30	177.30	Wet	Cylindric glass vessels	1981–2004	Zhang et al. (2010)
Golmud	94.90	36.42	278.76	278.76	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Delingha	97.37	37.37	293.79	293.79	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)

Maduo	98.22	34.92	416.23	416.23	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Jiayuguan	98.23	39.82	211.68	211.68	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Jiuquan	98.48	39.92	320.22	320.22	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Jiuquan1	98.50	39.75	204.72	204.72	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
BH	99.74	37.04	229.64	229.64	Wet	Cylindric glass vessels	2009.6–2010.5	Wan et al. (2012)
GC	100.11	37.25	256.92	256.92	Wet	Cylindric glass vessels	2009.6–2010.5	Wan et al. (2012)
Zhangye1	100.43	38.91	165.24	165.24	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Gonghe	100.62	36.27	238.76	238.76	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Zhangye	100.63	38.93	352.84	352.84	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Waliguan	100.92	36.30	64.58	64.58	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Xining	101.75	36.57	281.40	986.04	Wet	Cylindric glass vessels	1981–2004	Zhang et al. (2010)
Tongren	102.02	35.52	108.53	108.53	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Pingan	102.10	36.50	273.70	273.70	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Jinchang	102.20	38.50	290.22	290.22	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Xiasifen	102.27	35.91	496.80	496.80	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Haicangsi	102.27	37.96	332.04	332.04	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Wuwei	102.67	37.92	498.64	498.64	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Jiuzhoutai	103.20	35.97	569.40	744.45	Dry	Cylindric glass vessels	2013.3–2014.8	Wang et al., 2015
Chaiqiao	103.24	35.62	202.08	202.08	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Linxia	103.30	35.97	256.57	256.57	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Gaolan	103.78	36.22	133.00	133.00	Wet	Cylindric glass vessels	1998–2000	Liu et al. (2004)
Lanzhou	103.88	36.05	327.02	327.02	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Yuzhong	104.09	35.87	182.40	182.40	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Silongkou	104.40	36.44	416.76	416.76	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Shapotou	104.57	37.27	1186.19	1545.48	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Dingxi1	104.62	35.58	149.64	149.64	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Dingxi	104.62	35.58	281.63	370.73	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Wudu	104.92	33.39	107.28	107.28	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Haiyuan	105.64	36.56	534.08	534.08	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Alxa Left Banner	105.67	38.83	763.50	996.53	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Tianshui	105.75	34.58	180.86	180.86	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Tongxin	105.94	36.97	1081.11	1081.11	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Tianshui1	106.00	34.36	72.48	72.48	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Yinchuan	106.17	38.56	410.00	410.00	Wet	Cylindric glass vessels	1981–2004	Zhang et al. (2010)
Guyuan	106.20	36.00	238.32	314.48	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Wuzhong	106.21	37.99	349.66	349.66	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Jingyuan	106.33	35.50	227.70	227.70	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Lingwu	106.34	38.10	234.14	234.14	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Helan	106.35	38.55	457.13	457.13	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Dawukou	106.37	39.01	226.35	226.35	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Kongtongshan	106.52	35.55	132.12	132.12	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Pingluo	106.55	38.89	856.78	856.78	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Pingliang	106.67	35.55	256.94	256.94	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Taole	106.69	38.82	804.91	804.91	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Huinong	106.78	39.25	406.76	406.76	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Wulate County	106.98	41.45	61.31	84.60	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Dengkou	107.00	40.33	731.10	954.45	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Huan County	107.30	36.59	226.42	247.91	Dry	Plastic box	1995.9–1996.8	Sun et al. (2001a)

Yanchi	107.41	37.78	321.54	321.54	Wet	Cylindric glass vessels	2004	Zhao et al. (2005)
Etuokeqian Banner	107.48	38.18	69.87	95.71	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Qingyang	107.60	35.70	97.94	132.17	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Xifeng	107.64	35.73	327.91	125.32	Dry	Plastic box	1995.9–1996.8	Sun et al. (2001)
Bin County	108.07	35.05	714.39	139.34	Dry	Plastic box	1995.9–1996.8	Sun et al. (2001a)
Xunyi	108.30	35.17	92.70	125.36	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Liquan	108.43	34.50	659.73	126.48	Dry	Plastic box	1995.9–1996.8	Sun et al. (2001a)
Hanggin Banner	108.73	39.85	42.85	60.62	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Uxin Banner	109.03	38.38	388.68	509.75	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Fu County	109.38	36.00	158.19	210.42	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Pucheng	109.58	34.95	120.66	161.68	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Damao County	110.42	41.72	325.94	428.27	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Shenmu	110.43	38.82	636.05	831.01	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Ji County	110.68	36.10	75.64	103.21	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Hohhot	111.58	40.81	145.10	145.10	Wet	Cylindric glass vessels	1981–2004	Zhang et al. (2010)
Siziwang Banner	111.68	41.37	86.09	116.78	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Gu County	111.92	36.27	181.28	240.40	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Suniteyou Banner	112.65	42.75	287.04	377.75	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Chayouqian Banner	113.22	40.80	476.82	624.22	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Yanggao	113.77	40.37	87.12	118.12	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Zhangbei	114.70	41.16	169.04	169.04	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Abag Banner	114.95	44.02	156.77	208.57	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Xuanhua	115.09	40.61	56.40	56.40	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Taipusi Banner	115.27	41.88	132.21	176.68	dry	cylindric glass vessels	2001.4–2002.3	Li (2008)
Huailai	115.50	40.40	180.79	180.79	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Chicheng	115.82	40.91	59.84	59.84	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Fengning	116.64	41.21	74.91	74.91	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Xinlinriver	116.65	43.63	22.35	22.35	Wet	Cylindric glass vessels	1990.5–1994.12	Wang et al. (2000)
Luanping	117.33	40.92	15.61	15.61	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Keshiten Banner	117.53	43.25	81.25	110.49	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Longhua	117.72	41.30	55.20	55.20	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Neiman	120.65	42.85	257.38	339.23	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Nanhu Park	125.30	43.85	259.40	259.40	Wet	Cylindric glass vessels	1984–1993	Wang et al. (1997)

(*Notes:* Lon. refers to longitude of the site; Lat. refers to latitude of the site; dry method refers to the surface which has nothing; wet method refers to the surface which has a free water or glycerol layer; marble method refers to the surface which has two or one superimposed layers of marbles; In the study of Groll et al. (2013), the height of artificial grass is approximately 3 cm which is equal to the marble method; units: $g\,m^{-2}$).

Appendix B. The sites of mean seasonal atmospheric deposition in different regions

Site	Lon. (° E)	Lat. (° N)	Spring	Calibration spring	Summer	Calibration summer	Autumn	Calibration autumn	Winter	Calibration winter	Collection method	Collectors	Monitoring period	References
Karachi	62.97	25.26	76.98	76.98	78.66	78.66	45.98	45.98	28.48	28.48	Wet	Cylindrical plastic container	1980–1985	Beg et al. (1991)
Peshawar	71.58	34.02	331.04	331.04	405.41	405.41	298.56	298.56	241.83	241.83	Wet	Cylindrical plastic container	1992–1998	Khan et al. (2003)
Quetta	67.00	30.20	494.95	494.95	577.25	577.25	476.96	476.96	493.54	493.54	Wet	Cylindrical plastic container	1997–2002	Muhammad (2009)
Yazd	54.36	31.80	–	–	–	–	12.32	12.32	–	–	Wet	Cylindrical containers	2005.8–2006.3	Nabizadeh et al. (2007)
Kashgar	75.97	39.44	76.28	76.28	86.13	86.13	39.90	39.90	50.05	50.05	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Yarkent	77.26	38.38	151.18	151.18	55.35	55.35	51.43	51.43	139.41	139.41	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Yecheng	77.44	37.88	138.68	138.68	115.48	115.48	54.72	54.72	139.51	139.51	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Pishan	78.28	37.60	112.93	112.93	118.71	118.71	16.16	16.16	48.98	48.98	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Kalpin	79.03	40.47	47.40	47.40	25.06	25.06	35.98	35.98	43.10	43.10	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Hotan	79.93	37.11	160.00	160.00	205.93	205.93	80.59	80.59	28.13	28.13	Wet	Cylindrical glass	2000–2012	Zhang et al. (2015a)
Asku	80.26	41.17	29.46	29.46	20.67	20.67	72.35	72.35	31.01	31.01	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Cele	80.82	36.99	414.57	414.57	315.58	315.58	61.81	61.81	66.33	66.33	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Alar	81.28	40.51	30.67	30.67	33.79	33.79	63.68	63.68	26.51	26.51	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Minfeng	82.68	37.04	121.88	121.88	107.69	107.69	30.09	30.09	45.13	45.13	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Jinghe	82.89	44.60	63.00	63.00	13.90	13.90	8.48	8.48	38.25	38.25	Wet	Cylindrical glass	2000–2012	Zhang et al. (2015b)
Tazhong	83.39	38.58	561.63	561.63	578.53	578.53	94.96	94.96	89.14	89.14	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Bachu	84.10	39.75	65.07	65.07	54.83	54.83	31.34	31.34	45.07	45.07	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Luntai	84.24	41.74	72.19	72.19	101.53	101.53	27.55	27.55	48.21	48.21	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Tikanlik	87.42	40.39	57.56	57.56	70.15	70.15	31.47	31.47	23.45	23.45	Wet	Cylindrical glass	2008–2010	Wang (2012a)
Charkhlik	88.26	38.99	63.66	63.66	44.18	44.18	22.72	22.72	40.13	40.13	Wet	Cylindrical glass	2008–2010	Wang (2012a)

Golmud	94.90	36.42	30.41	91.25	22.30	67.04	19.62	59.40	61.78	62.64	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Delingha	97.37	37.37	36.54	110.70	30.54	91.46	16.77	50.08	42.24	42.50	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Maduo	98.22	34.92	36.98	110.39	41.01	110.39	28.18	84.88	97.74	97.08	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Jiayuguan	98.23	39.82	59.72	59.72	68.81	68.81	32.87	32.87	52.03	52.03	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Jiuquan	98.50	39.75	66.63	66.63	62.24	62.24	36.27	36.27	39.67	39.67	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
BH	99.74	37.04	108.36	108.36	28.16	28.16	26.05	26.05	67.07	67.07	Wet	Cylindric glass vessels	2009.6–2010.5	Wan et al. (2012)
GC	100.11	37.25	27.74	27.74	51.83	51.83	137.22	137.22	40.12	40.12	Wet	Cylindric glass vessels	2009.6–2010.5	Wan et al. (2012)
Zhangye	100.43	38.91	50.06	50.06	45.88	45.88	33.90	33.90	35.47	35.47	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Gonghe	100.62	36.27	29.32	87.36	19.38	57.68	11.93	35.34	56.89	56.12	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Waliguan	100.92	36.30	8.45	25.15	5.23	15.57	3.95	11.80	11.70	11.62	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Xining	101.75	36.57	131.17	396.62	73.16	222.35	50.49	153.99	209.81	210.33	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Tongren	102.02	35.52	12.40	37.24	8.59	25.30	7.58	22.55	22.83	22.79	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Pingan	102.10	36.50	28.58	28.58	30.38	30.38	19.56	19.56	38.16	38.16	Wet	Cylindric glass vessels	2004–2010	Gao et al. (2013)
Xiasifen	102.27	35.91	136.51	136.51	144.46	144.46	76.50	76.50	63.22	63.22	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Haicangsi	102.27	37.96	139.81	139.81	95.96	95.96	45.10	45.10	48.92	48.92	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Sheqiao	103.24	35.62	72.00	72.00	46.27	46.27	40.15	40.15	45.44	45.44	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Gaolan	103.78	36.22	113.01	113.01	48.63	48.63	40.96	40.96	67.40	67.40	Wet	Cylindric glass vessels	1998–2000	Liu et al. (2004)
Yuzhong	104.09	35.87	64.11	64.11	47.96	47.96	37.73	37.73	32.74	32.74	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Silongkou	104.40	36.44	141.69	141.69	118.67	118.67	66.25	66.25	83.94	83.94	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Dingxi	104.50	35.50	81.98	81.98	35.50	35.50	12.12	12.12	45.81	45.81	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Shapotou	104.57	37.27	674.59	881.06	338.68	444.82	81.76	111.16	91.16	123.36	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Dingxi1	104.62	35.58	67.04	67.04	33.30	48.22	21.14	21.14	31.76	31.76	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Wudu	104.92	33.39	34.93	34.93	29.78	43.65	19.10	19.10	25.08	25.08	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Alxa Left Banner	105.67	38.83	415.34	544.38	273.13	359.69	9.97	17.92	65.06	89.47	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)

Maijishan	106.00	34.36	28.85	28.85	16.80	26.79	12.94	21.78	14.62	14.62	Wet	Cylindric glass vessels	1986–1995	Zhang and Kang (1999)
Guyuan	106.20	36.00	127.96	171.16	43.09	60.94	22.37	34.03	44.90	63.29	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Pingliang	106.52	35.55	53.85	53.85	24.44	24.44	22.63	22.63	31.44	31.44	Wet	Cylindric glass vessels	1986–2000	Jia et al. (2012)
Wulatehou Banner	106.98	41.45	12.28	20.92	27.00	40.04	15.12	24.61	6.91	13.95	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Dengkou	107.00	40.33	225.10	297.31	241.81	319.01	77.40	105.49	186.79	247.56	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Huan county	107.30	36.59	76.12	113.91	80.03	110.87	29.28	14.43	40.99	20.40	Dry	Plastic box	1995.9–1996.8	Sun et al. (2001a)
Etuokeqian Banner	107.48	38.18	36.58	36.58	23.55	23.55	2.72	2.72	7.02	7.02	Wet	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Qingyang	107.60	35.70	35.95	35.95	18.39	18.39	4.19	4.19	39.41	39.41	Wet	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Xifeng	107.64	35.73	83.93	45.30	126.87	50.20	48.80	18.42	68.32	25.90	Dry	Plastic box	1995.9–1996.8	Sun et al. (2001a)
Bin county	108.07	35.05	40.95	58.16	22.59	34.31	19.53	30.34	20.05	31.02	Dry	Plastic box	1995.9–1996.8	Sun et al. (2001a)
Xunyi	108.30	35.17	55.09	76.52	25.48	38.06	7.59	14.83	4.54	10.87	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Liquan	108.43	34.50	20.34	31.39	23.40	35.36	19.17	29.87	31.05	45.30	Dry	Plastic box	1995.9–1996.8	Sun et al. (2001a)
Hangjin Banner	108.73	39.85	21.79	33.27	15.63	25.27	4.69	11.06	0.74	5.94	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Uxin Banner	109.03	38.38	303.75	399.45	47.34	66.45	25.82	38.51	11.77	20.26	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Fu county	109.38	36.00	102.31	137.84	31.59	46.00	10.02	17.99	14.27	23.51	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Pucheng	109.58	34.95	42.29	59.90	40.60	57.70	24.68	37.03	13.09	21.97	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Damao Banner	110.42	41.72	101.17	136.36	180.21	239.01	23.21	35.12	21.34	32.69	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Shenmu	110.43	38.82	305.06	401.16	190.01	251.74	50.96	71.16	90.02	121.88	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Ji county	110.68	36.10	49.26	68.95	18.51	29.01	3.34	9.31	4.53	10.86	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Siziwang Banner	111.68	41.37	27.13	40.21	44.62	62.92	5.95	12.70	8.39	15.87	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Gu county	111.92	36.27	63.30	87.18	54.69	76.00	21.29	32.62	42.00	59.52	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Suniteyou Banner	112.65	42.75	110.68	148.71	74.74	102.04	29.04	42.69	72.58	99.23	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Chayouqian Banner	113.22	40.80	224.88	297.03	108.14	145.42	47.21	66.29	96.59	130.42	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Yanggao	113.77	40.37	19.24	29.96	13.58	22.61	25.25	37.77	29.05	42.70	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Zhangbei	114.70	41.16	75.69	75.69	9.45	9.45	26.96	26.96	56.94	56.94	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Abag Banner	114.95	44.02	62.67	86.36	27.06	40.12	17.84	28.14	49.20	68.87	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)

Xuanhua	115.09	40.61	24.27	24.27	7.54	7.54	9.13	9.13	15.46	15.46	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Taipusi Banner	115.27	41.88	81.64	111.00	16.20	26.01	5.89	12.62	28.48	41.96	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Huailai	115.50	40.40	63.87	87.92	57.70	79.91	31.48	45.86	27.74	41.00	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Chicheng	115.82	40.91	22.51	22.51	10.33	10.33	5.66	5.66	21.34	21.34	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Fengning	116.63	41.22	31.08	31.08	6.90	6.90	4.30	4.30	9.74	9.74	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Xinlinriver	116.65	43.63	6.19	6.19	8.45	8.45	7.19	7.19	2.17	2.17	Wet	Cylindric glass vessels	1990.5–1994.12	Wang et al. (2000)
Luanping	117.33	40.92	5.94	5.94	2.37	2.37	2.69	2.69	4.60	4.60	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Hexigten Banner	117.53	43.25	60.07	82.99	9.17	16.88	3.91	10.05	8.10	15.49	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Longhua	117.72	41.30	26.72	26.72	3.57	3.57	8.99	8.99	15.92	15.92	Wet	Cylindric polyethylene container	2008.3–2009.2	Tang et al. (2011)
Naiman	120.65	42.85	147.94	197.10	67.94	93.21	20.38	31.44	21.12	32.40	Dry	Cylindric glass vessels	2001.4–2002.3	Li (2008)
Nanhu Park	125.30	43.85	78.58	78.58	41.66	41.66	41.42	41.42	97.73	97.73	Wet	Cylindric polyethylene container	1984–1993	Wang et al. (1997)
Bikaner	73.22	28.01	381.00	483.56	–	–	–	–	14.10	19.13	Marble	Plastic tray	2001	Yadav and Rajamani (2004)
Jhunjhunu	75.25	28.06	103.02	131.68	–	–	–	–	12.30	16.85	Marble	Plastic tray	2001	Yadav and Rajamani (2004)
Delhi	77.12	28.38	48.00	62.04	–	–	–	–	9.30	13.05	Marble	Plastic tray	2001	Yadav and Rajamani (2004)
Garhmumktesar	77.8	28.42	–	–	–	–	–	–	14.40	19.51	Marble	Plastic tray	2001	Yadav and Rajamani (2004)

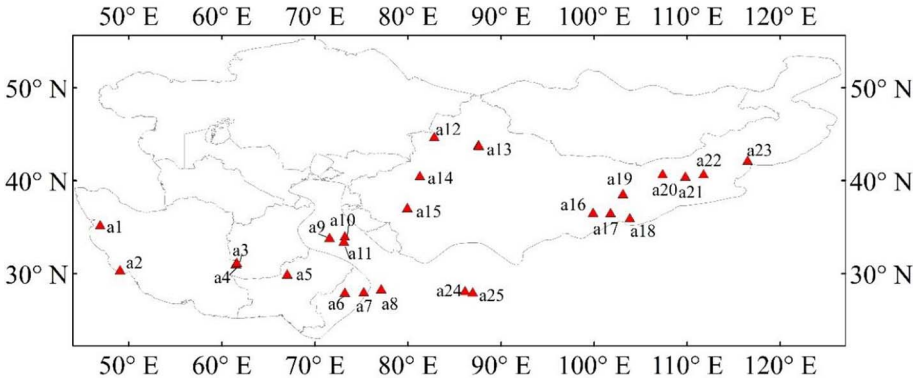
(*Notes:* Lon refers to longitude of the site; lat refers to latitude of the site; dry method is refer to the surface which has nothing; wet method is refer to the surface which has a free water or glycerol layer; marble method is refer to the surface which has two or one superimposed layers of marbles; In the study of Groll et al. (2013), the height of artificial grass is approximately 3 cm which is equal to the marble method; – refers to nodata; units: g m^{-2}).

Appendix C. The composition of aeolian deposition in different regions

Region	Site	Ca	Al	Mg	Fe g kg^{-1}	Zn	Cu	Cd	Ni	Pb	Mn	Co	Cr	V mg kg^{-1}	Analysis method	Data sources
S2	a1	–	–	14.0	–	–	43.0	–	–	–	840.0	–	–	–	FAAS	Khuzestani and Souri (2013)
	a2	–	74.0	42.8	–	109.3	33.5	–	38.3	25.0	323.7	–	–	164.3	ICP-AES	Abdollahi et al. (2013)
	a3	–	–	–	–	57.0	11.0	–	18.0	10.0	–	–	70.0	69.0	XRF	Rashki et al. (2013)
	a4	–	–	–	–	51.0	11.0	–	16.0	10.0	–	–	84.0	69.0	XRF	Rashki et al. (2013)
	a5	–	–	–	–	602.8	–	–	294.6	2667.0	525.0	35.0	72.1	–	AAS	Muhammad (2009)
	a9	–	–	–	–	763.0	–	–	358.0	525.0	637.0	54.0	83.0	–	AAS	Saeed et al. (1998)
	a10	–	–	–	–	554.6	446.0	55.8	476.3	943.0	533.0	–	–	–	AAS	Hussain (2001)
	a11	–	–	–	–	8.3	–	–	5.6	22.7	–	–	–	–	AAS	Khan et al. (2003)
S3	a6	64.1	119.0	22.0	38.0	56.0	20.0	–	44.0	35.0	1000.0	–	79.0	72.0	ICP-AES	Yadav and Rajamani (2004,2006)
	a7	52.1	113.0	15.0	31.0	64.0	141.0	–	22.9	33.1	1000.0	–	65.4	–	ICP-AES	Yadav and Rajamani (2004,2006)
	a8	53.5	135.0	26.0	48.0	166.0	61.0	–	69.0	228.0	1000.0	–	98.0	–	ICP-AES	Yadav and Rajamani (2004,2006)
S5	a12	23.0	0.03	2.3	–	106.9	22.7	0.21	–	17.8	–	–	95.3	–	ICP-MS	Zhang et al. (2015)
	a13	–	–	8.1	–	763.7	55.4	1.3	49.3	34.9	429.3	–	66.7	–	ICP-AES	Zhang et al. (2014a,b)
S6	a14	–	–	–	1.9	75.4	35.0	–	–	–	395.0	–	7.4	–	AAS	Mo et al. (2012)
	a15	42.8	–	13.1	–	1162.5	24.7	–	44.4	–	565.3	–	43.7	–	NAA	Li (2012)
S7	a16	15.8	12.2	14.0	–	21.9	22.3	–	–	228.9	2990.0	–	–	–	ICP-MS	Wan et al. (2012)
	a17	–	93.3	38.8	53.4	1000.0	56.4	5.5	44.8	51.6	1100.0	–	–	–	XRF	Tang et al. (2013)
S8	a18	105.0	8.9	19.7	52.3	520.1	72.7	–	38.6	135.87	825.56	13.8	80.7	88.8	XRF	Yang et al. (2002)
	a19	–	–	–	–	75.8	28.4	0.22	33.5	37.69	–	12.4	68.0	–	ICP-MS	Wang et al. (2010)
S9	a22	–	–	–	57.9	247.1	55.8	0.6	30.9	77.1	661.1	–	76.1	–	ICP-MS	Wang (2012b)
	a21	–	106.1	–	70.2	87.2	23.1	0.2	22.9	33.1	596.3	10.9	65.4	–	ICP-MS	Wang (2012b)
	a20	–	–	–	–	–	65.8	0.7	–	110.0	–	–	98.4	–	ICP-MS	Wang (2012b)
S10	a23	–	–	–	15.3	97.0	19.7	–	18.4	38.3	538.0	9.2	29.7	35.3	ICP-MS	Qiao et al. (2013)
H*	a24	–	–	–	–	0.718	0.091	0.004	0.061	0.170	0.001383	0.024	0.129	0.097	ICP-SFMS	Liu et al. (2011)
	a25	–	–	–	–	0.475	0.076	0.002	0.085	0.077	0.001302	0.036	0.104	0.111	ICP-MS	Zhang et al. (2009)

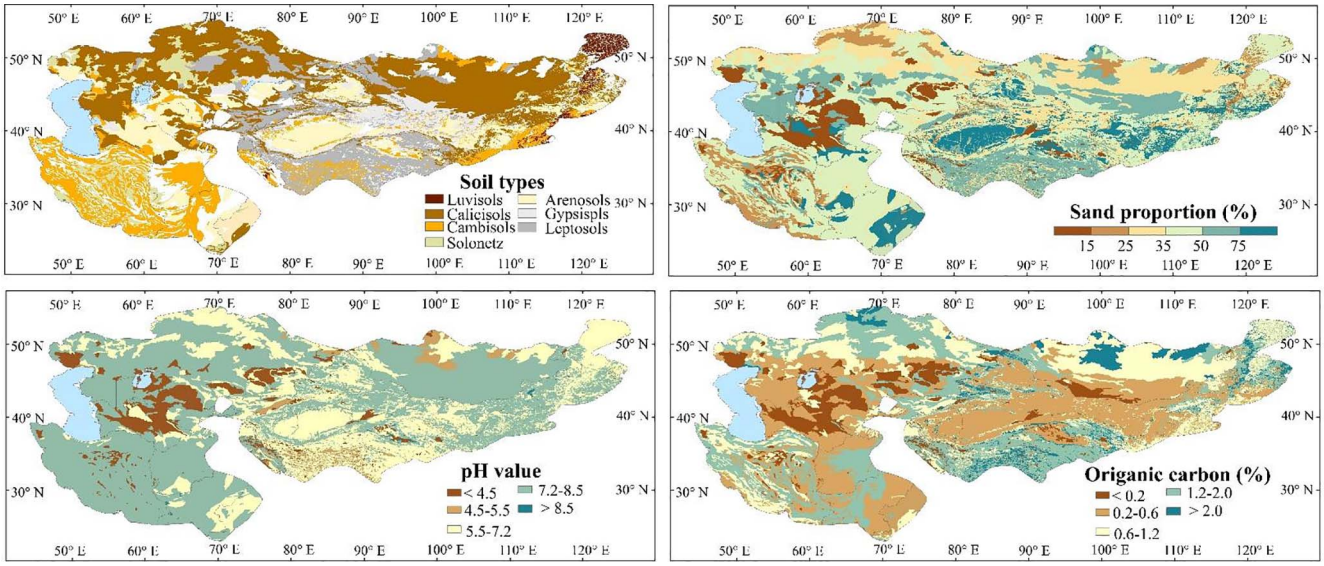
Notes: H refers to High Mountain; ∗: ng g^{-1}; –: no data; FAAS refers to the method of Flame Atomic Absorption Spectrophotometer; ICP-AES refers to the method of Inductively Coupled Plasma Atomic Emission Spectrophotometry; XRF refers to X-ray fluorescence; AAS refers to Atomic Absorption Spectrophotometer; ICP-MS refers to Inductively Coupled Plasma mass spectrometry; NAA refers to neutron activation analysis; ICP-SFMS refers to inductively coupled plasma sector field mass spectroscopy.

Appendix D. The locations of sites described in the main text



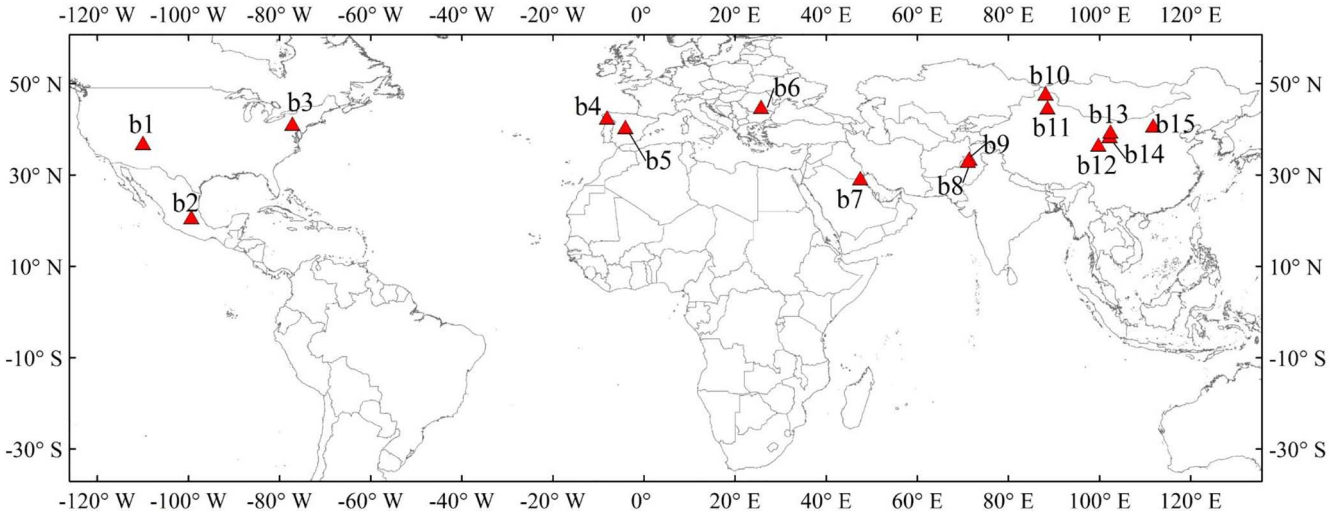
Notes: a1: Kurdistan; a2: Imam Khomeini Port; a3: Sistan A; a4: Sistan B; a5: Quetta; a6: Bikaner; a7: Jhunjhunu; a8: Delhi; a9: Peshawar; a10: Islamabad; a11: Abbotabad; a12: Ebinur Lake; a13: Urumqi; a14: Alar region; a15: Hotan; a16: Qinghai Lake; a17: Xining; a18: Lanzhou; a19: Minqin; a20: Linhe; a21: Baotou; a22: Hohhot; a23: Otindag desert; a24: Cho Oyu; a25: Qomolangma.

Appendix E. The soil characteristics in arid Asia



Notes: soil pH and organic carbon data is reference to the soil properties about the 0-30 cm soil; the data is from HWSD (version 1.1).

Appendix F. The locations of sites described in the main text



Notes: b1: Colorado Plateau; b2: Zimapan region; b3: Pennsylvania; b4: western Galicia; b5: Iberian Peninsula; b6: Dambovita; b7: Kuwait desert; b8: Kohat; b9: Karak District; b10: Aletai city; b11: Gurbantunggut Desert; b12: Qinghai Lake; b13: Alxa Desert; b14: Jinchang; b15: Hohhot.

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